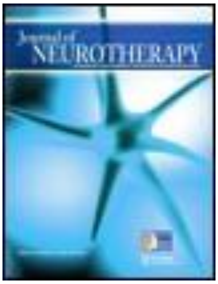

Journal of Neurotherapy: Investigations in Neuromodulation, Neurofeedback and Applied Neuroscience

QEEG

David A. Kaiser PhD [a]

[a] Sterman-Kaiser Imaging Laboratory , P.O. Box 491956, Los Angeles, CA, 90049, USA

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QEEG:
State of the Art, or State of Confusion

David A. Kaiser, PhD

ABSTRACT. Recent advances in technology have resulted in a proliferation of quantitative EEG applications. The availability of few formal methodological standards threatens to transform this computational and technical freedom into a permanent source of confusion and incompatibility. Common methodological and analytical parameters of topographic EEG research are reviewed, with the goal of eventual formalization of methodological procedures for the field. *[Article copies available for a fee from The Haworth Document Delivery Service: 1-800-342-9678. E-mail address: <getinfo@haworthpressinc.com> Website: <http://www.HaworthPress. com>]*

KEYWORDS. Quantitative EEG, QEEG, methodology, methods, spectral analysis, controversy

Despite reports of electrical activity in animal brains in the late 19th century (Caton, 1895), the existence of brain potentials remained largely

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David A. Kaiser, PhD, is affiliated with the Sterman-Kaiser Imaging Laboratory, P.O. Box 491956, Los Angeles, CA 90049 (E-mail: dakaiser@skiltopo.com).

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unknown and unexplored in humans until 1929 when Hans Berger published his first report on electrical activity of the human brain, which he designated the "Elektenkephalogram," or EEG (Remond & Lairy, 1972; Gevins & Schaffer, 1980). Five years passed before his findings were confirmed in the English-speaking world (Adrian & Matthews, 1934; Petsche, 1989). By 1934 about three-quarters of what we now know about human EEG, particularly for the alpha or dominant rhythm, was already known generally to Berger. Berger identified and labeled alpha and beta activity, applied Fourier analysis to these signals, described alpha blocking (an abrupt suspension of alpha waves) which he correctly recognized was an information processing response (in today's terms) and was not dependent upon respiratory, vascular, or motoric responses as others thought (confirmed by Bohdanecky, Indra, Lansky, & Radil-Weiss, 1984; Ray & Cole, 1985). He believed that the amount of alpha activity reflected the extent of attentional and cognitive processing–what most believe today. About the only issue he didn't pursue (or care much about) were the brain mechanisms responsible for generating these rhythms.

Half a century passed and few wrinkles were added to our general knowledge of human EEG. It didn't increase significantly until another complex electrical system entered the ongoing investigation. The rapid advance of computer technology in the 1980s and '90s has been a great yet troublesome boon for EEG research. Anyone with a computer and a set of amps could now investigate the three-pound universe. Inexpensive and sophisticated acquisition and analysis technology has created a surge in quantitative EEG applications and users. Much knowledge has emerged from this computational freedom, but more is mired in confusion and a proliferation of incompatible results. A lack of standards in basic domains of quantitative EEG research (e.g., epoch parameters, data transformations) continues to confound the effectiveness of this exceptional assessment tool and limit its acceptance in what should be routine implementation in neurological, psychiatric, and educational circumstances.

METHODOLOGICAL ISSUES

Quantitative electroencephalography has earned a reputation of being noisy, unreliable, and imprecise in the minds of psychologists, neurologists, and laypersons alike (Nuwer, 1988; Begley, 1992). It is not a lack of methodological rigor but a lack of methodological standards, which reinforces this erroneous characterization. A researcher interested in analyzing the quantitative EEG (QEEG) during behavioral and mental processes confronts a gauntlet of largely arbitrary methodological choices about reference electrodes, recording electrodes, epoch parameters, windowing function, bandwidths, spectral estimates, and artifact control (see Table 1). Non-spectral analysis has its own sets of methodological alternatives to choose from (e.g., Gregson, Britton, Campbell, & Gates, 1990). Different methodological configurations can generate incompatible, or worse, conflicting findings and conclusions (e.g., Davidson, Chapman, Chapman, & Henriques, 1990). Yet when methodologies are comparable across studies, QEEG results prove highly reliable, especially for challenge conditions (McEvoy, Smith, & Gevins, 2000; Fernandez, Harmony, Rodriguez, Reyes, Marosi, & Bernal, 1993; Salinsky, Oken & Morehead, 1991). This essay will briefly survey methodological issues inherent in spec-

TABLE 1. Methodological issues in spectral analysis of EEG

1. Acquisition (Hardware-related)
    a. Reference method (e.g., ipsilateral, linked)
    b. Montage (active recording locations)
    c. Maximum impedance
    d. Minimum number of electrodes
2. Acquisition (Software-related)
    a. Epoch interval
    b. Epoch overlap (e.g., 0%, 50%, 75%)
    c. Window function (e.g., Hanning, rectangle)
    d. Task duration
    e. Frequency bands
    f. Artifact control
    g. Data transform (e.g., log, power, relative)
    h. Spectral parameter (e.g., amplitude, coherence)
3. Analysis
    a. Reliability (e.g., test-retest)
    b. Baseline and control conditions
    c. Statistical methods (parametric, non-parametric)
    d. Statistical corrections (e.g., Huynh-Feldt, Bonferroni)

tral analysis of human EEG and propose a set of standards, wherever possible, that may be used to frame future discussion and debate.

Recording References

Each EEG recording reference has its own set of advantages and disadvantages. Linking reference electrodes from two mastoids or earlobes provide a non-lateralized reference (Miller, Lutzenberger, & Elbert, 1991). This common method reduces the likelihood of artificially inflating activity in one hemisphere. But the use of linked-ears references had been criticized by Nunez (1991) because he claims that the "effective" reference will drift away from the midline plane if the electrical resistance at each electrode differs, the phenomenon called "shunting." Maintaining small contact resistances compared to amplifier input impedances (e.g., 5-10 K ohms) reduces resistance variance to reasonable levels. Within-group comparisons are also less affected by systematic reference problems, such as shunting. Nevertheless, Nunez recommends ipsilateral references or reference-free techniques in lieu of linked references (Nunez, 1991; Nunez, Silberstein, Cadusch, & Wijesinghe, 1993).

In response to Nunez's recommendation, the author performed a simple experiment in which linked-ear and ipsilateral-ear references were compared for eyes closed (EC) and eyes open (EO) conditions in two subjects. For either condition alpha activity did differ slightly (less than 2%) between reference types. Substantial differences between reference types, however, were noted in the beta range (12 Hz and above). This finding does not warrant the rejection of the popular linked-ear reference, though more subjects are required to further clarify differences between reference types.

Linked-ears and ipsilateral-ear montages rely on physical references. Electrical potentials may seep into a physical reference and transform an otherwise electrically neutral area into an active site, producing topographic distortion. This is evident in the topographic distribution associated with the linked-ear montage. The presence of cortical activity in each earlobe manifests less activity in lateral electrodes while maximizing activity in the midsagittal plane (Etevenon, 1986). Nuwer (1988) proposes that researchers run several references in succession to identify active leads, an impractical and costly approach. Active references, if stable across recording conditions, are not problematic for within-subject comparisons.

Reference-free techniques, such as common average references or source derivation, do not suffer from problems associated with an actual physical reference (Duffy, 1986). Local common average references are especially accurate for small-localized regions (Pfurtscheller, 1988) but this reference is poor for extensive topographic evaluations (Duffy & Maurer, 1989). Source-derived and Laplacian constructions require multiple electrodes for each brain area and are inaccurate for regions with few neighboring electrodes, such as lateral or posterior areas (Nuwer, 1988; Duffy, 1986; Gevins, 1984). Laplacian derivations also generate hard to interpret complexities (Duffy & Maurer, 1989) with little standardization between laboratories (e.g., Nunez et al., 1993; Gundel & Wilson, 1992; Pfurtscheller, 1988).

One hundred relevant EEG studies between 1965 and 1994 were surveyed by the author as part of an unpublished doctoral thesis (Kaiser, 1994) in order to assess the prevalent methodologies in quantitative EEG. Seven different references were described in this literature. Referencing to linked ears or vertex were predominant. Eighty-four percent of all studies involved referential recordings, in which scalp electrodes are connected to a common neutral site or sites, such as the earlobe or base of the neck. The remaining studies employed bipolar montages, which involves connecting pairs of scalp electrodes together without reference to a common inactive lead. Unfortunately, this second configuration obscures localized functional activity (Gevins, 1986). Dissimilar reference configurations can produce strikingly distinct topographies, reinforcing the need for reference standardization (Pfurtscheller, 1988; Pfurtscheller & Klimesch, 1990; Lehmann, 1989; Davidson et al., 1990). As it happens, no current reference technique is worthy of universal application (Duffy, 1986).

Recording Electrodes

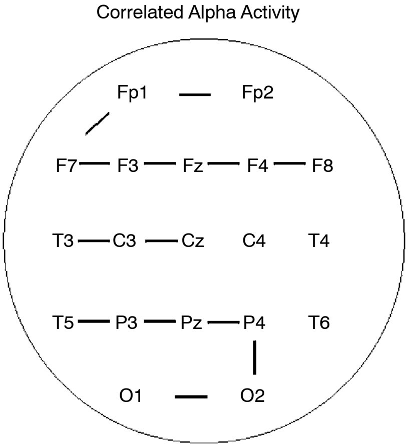
The international 10-20 system of electrode placement standardized physical placement and designations of electrodes on the scalp (Jasper, 1958). This coordinate system divides the head into proportional distances from prominent skull landmarks (nasion, preauricular points, inion) so as to provide adequate coverage of all regions of the brain. Electrode placements are labeled for the adjacent brain area to facilitate communication between researchers and laymen alike. The 10-20 system owes its endurance in part to its simplicity and the fortuitous division of the head into functional regions that remain relevant to human information processing research given the present state of technology. According to CT-scan evidence, F3 and F4 overlays Brodmann's area 46, C3 and C4 Brodmann's area 4, and P3 and P4 Brodmann's area 7 (Homan, Herman, & Purdy, 1987). Still, many researchers continue to position recording electrodes arbitrarily, without regard to standardized coordinate systems (e.g., Goodman & Mulholland, 1988; Pfurtscheller & Klimesch, 1990). Others use a minimum number of electrodes, obviating topographic differences (e.g., Davidson et al., 1990).

A familiar argument against usefulness of topographic EEG in research or clinical settings is the supposed poor spatial resolution of scalp electrodes (Nunez et al., 1993; Lorig & Schwartz, 1989). The problem arises not from the fact that scalp electrodes record activity from a large pool of neurons simultaneously (Nunez, 1981), but that the EEG signal can be smeared or filtered as it passes through meninges, calvarium, and unrelated cortical tissue. Although Gevins (1993) and others have attempted 128 scalp electrodes to increase spatial resolution, the technique does not address the primary concern, which is one of functional rather than physical resolution.

To address this problem, the author computed comodulation (i.e., correlation of spectral values) of neighboring sites for twenty subjects during an eyes closed condition. EEG magnitudes were averaged and normalized to reduce inter-subject variability. Log mean magnitude at each recording site was correlated to means at neighboring electrodes so as to identify whether there is significant smearing between proximal electrodes. If functional resolution were poor, correlations between electrodes would depend solely on physical proximity. Alpha activity at site P4 would resemble activity at all neighboring sites (T6, C4, O2) as readily as it mirrors activity in functionally related areas (Pz, P3). This was not the case (see Figure 1). Except for temporal regions, comodulation between neighboring electrodes across functional boundaries (e.g., parietal to temporal) was much smaller than comodulation within functional regions (e.g., left parietal to midline parietal), indicating that multiple distinct functional areas are assessed by topographic EEG (Kooi, 1971; Bullock & McClune, 1989).

The number of electrodes used in EEG research has steadily increased during the past thirty-five years to an average of twelve electrodes in recent years. During the same period, the number of subjects per study has gradually

FIGURE 1. Functional resolution of alpha activity for the eyes closed condition (n = 20). Lines indicate rho = 0.50 or higher correlations between proximal sites.

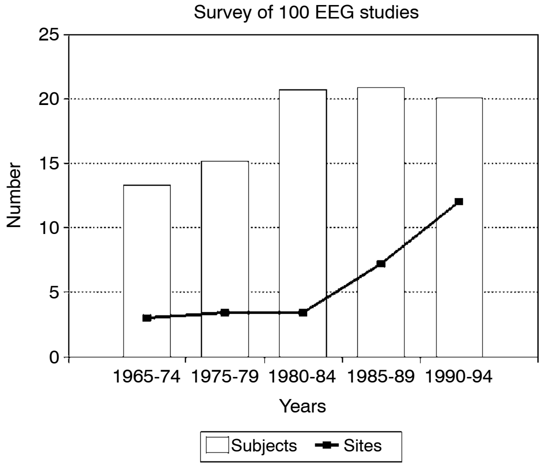


increased (in the 100-study survey, see Figure 2). Number and position of electrodes often varies as a function of research requirements, such as mapping of hemispheric dynamics or investigating focal activity (Etevenon, 1986). Notwithstanding, a proposed minimum of eight electrodes, over specific cortical areas, is recommended for studying higher cognitive functions and subsequent acceptance in psychophysiological and related journals. The recommended areas from which EEG is to be acquired include left and right regions of frontal, central, temporal, and parietal cortex (Kooi, 1971; Etevenon, 1986). More recording electrodes are likely necessary for detecting complex patterns of cortical activity, but more than twenty electrodes are unwarranted for most research goals (Duffy, 1986; Duffy & Maurer, 1989). This modest requirement should immediately enhance study compatibility as well as improve communication between EEG laboratories on the whole.

Frequency Analysis

EEG can be characterized as either non-periodic (spikes, random noise), non-sinusoidal and periodic (mu), or sinusoidal (alpha, delta) signals (Nunez, 1981). Spectral analysis minimizes the inherent redundancy in a periodic signal by evaluating frequency components of the EEG signals (Gevins, 1986; Etevenon, 1986; Kunkel, 1978). Using spectral analysis, also called frequency analysis, an EEG signal can be decomposed into constituent periodic components, usually by means of a set of filters or mathematical functions

FIGURE 2. Average number of subjects and recording sites in EEG studies for 5 or 10 year periods.



(e.g., Fourier analysis). Frequency analysis provides an efficient means of summarizing relevant information from longer records of EEG generated in clinical and research settings.

Using spectral analysis, researchers have formulated numerous indices of cerebral activity such as coherence, power, peak frequency, and alpha periodicity (Remond & Lairy, 1972; Nuwer, 1988; Sterman, Mann, Kaiser, & Suyenobu, 1994). Although a few scientists report and attempt to interpret as many as ten spectral indices or parameters for each recording session (e.g., de Rijke & Visser, 1989; Etevenon, 1986), the majority of published EEG analysis concerns a single spectral parameter or two (e.g., absolute and relative power). In addition to spectral parameters, researchers can define a wide range of frequencies to analyze. Some studies include a laundry list of spectral parameters for a dozen or more frequency bands, impressively diminishing the quality of the information communicated to the reader (e.g., Etevenon, Bertaut, Mitermite, & Eustache, 1989; Etevenon, 1986). Studies that concentrate on single spectral parameters for multiple frequency bands (e.g., Grillon & Buchsbaum, 1986) or multiple spectral parameters for a single frequency band are likely optimal for both experimenter and audience.

Spectral Bands and Parameters

Conventional frequency bands in EEG research are the following: 0-4 Hz (delta), 5-7 Hz (theta), 8-13 Hz (alpha) and 14 or more Hz (beta). A common and accepted practice in quantitative EEG analysis involves designating adjacent bands of 4 Hz intervals (e.g., 0-4 Hz, 4-8 Hz, 8-12 Hz, 12-16 Hz, 16-20 Hz) (cf. Hughes & John, 1999 for similar divisions). It is well known that wide frequency bands (more than 1 to 2 Hz intervals) encompass a variety of physiological processes (Lorig & Schwartz, 1989; Grillon & Buchsbaum, 1986) and many functions are better identified in narrower (e.g., 8-10 Hz, 11-13 Hz) frequency bands (Pfurtscheller & Klimesch, 1990; Gale & Edwards, 1983; Sterman et al., 1994). Yet no definitive division of the human EEG frequency range has been found. More than 20 arbitrary frequency boundaries have been specified in the literature for studying the alpha rhythm (e.g., 7.81-14.06 Hz, 7.03-12.89, 8-15 Hz; Etevenon, Eustache, Mitermite, Lepaisant, Lechevalier, & Zarifian, 1990; de Toffel & Autret, 1991; Ray & Cole, 1985). Lack of standardization in frequency bands fosters confusion between laboratory findings, but may be required due to the range of variables addressed by quantitative EEG (Remond & Lairy, 1972). Nevertheless, the use of traditional frequency bands is most appropriate for preliminary investigations and hypothesis testing.

The alpha rhythm refers to the dominant or peak frequency recorded from cortex, especially pronounced during non-processing, relaxed conditions (Berger, 1930). In the literature at least eighty-nine percent (probably one hundred percent if data are evaluated appropriately) of normal healthy results exhibit alpha activity, though magnitudes vary between individuals (Remond & Lairy, 1972). Most adults generate between 20 to 60 μV of alpha activity during eyes closed conditions (Kooi, 1971). Peak alpha frequency is fairly stable (10 ± 0.5 Hz) in most individuals during a single session and from day to day (Nuwer, 1988) and is consistent for various subject populations (Nunez, 1981; Kooi, 1971; Sterman et al., 1994). In Kaiser (1994), the mean and mode of the peak frequency recorded from 20 subjects during an eyes-closed baseline condition (EC2) was approximately 10 Hz (see Figure 3).

As seen in Figure 4, peak frequency exhibits topographic variability, with higher peak frequencies in posterior cortex (10.3-10.6 Hz) and lower peak frequencies in anterior cortex (9.7-10.3 Hz; cf. Gratton, Villa, Fabiani, Colombis, Palin, Bolcioni, & Fiori, 1992, for similar results). Nunez (1981) reported that ninety-six percent of peak frequencies fell between 8 and 12 Hz for one hundred thirty-five subjects. In this study, a frequency band of 8-12 Hz was used to measure alpha activity. Integer frequency boundaries were chosen in order to facilitate comparisons to other studies.

Numerical Transformations of Alpha Amplitude

Physiological data distributions are typically skewed, a fact that contradicts the normality assumption underlying the Analysis of Variance test (Duffy & Maurer, 1989). Deviations from normality in EEG data distributions arise from various origins (Kramer, 1991; Nuwer, 1988), including: (1) scale examined (e.g., power), (2) intrinsic biological mechanisms, (3) inter-subject heterogeneity, (4) artifacts, and (5) spectral parameters that are arbitrary and not biologically meaningful. Transformations such as log power (twice log magnitude) and the square root of power (magnitude) result in relatively normal distributions (Gasser, Bacher, & Mocks, 1982) whereas power distributions are usually skewed. Despite this information, the majority of studies continue to analyze power means.

Figure 5 shows three mathematical transformations of mean amplitude for high interest films. Squared transformation (power) result in highly skewed distributions for high interest conditions (Dmax = 0.17, $p < .01$; cf. Kolmogorov, 1941). Linear transformation (magnitude) result in moderately skewed distributions for high interest conditions (Dmax = 0.12, $p < .05$). Finally, logarithmic transformation (natural log of mean magnitude) result in relatively normal distributions (Dmax = 0.056, ns) and it has been shown that many psychological phenomena such as loudness correlate with the logarithm of physiological data (e.g., Baird, Berglund, Berglund, & Lindberg, 1991; Krueger, 1989).

FIGURE 3. Distribution of peak frequency recorded from 19 recording sites during an eyes closed baseline condition (n = 20). Dashed lines indicate mean and dotted lines indicate the 95% confidence interval.

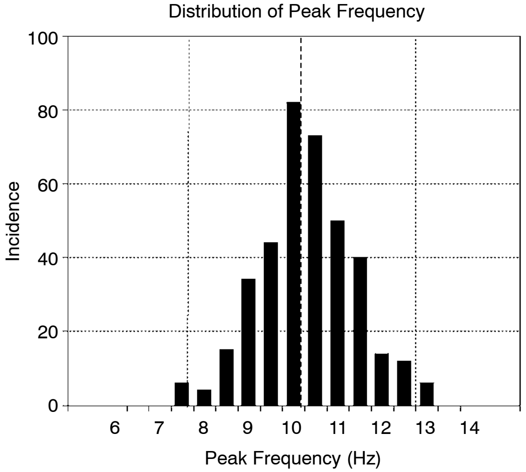


FIGURE 4. Topography of peak frequency for an eyes closed baseline (n = 20). Bars indicate 95% confidence interval. Note the greater variance at anterior regions.

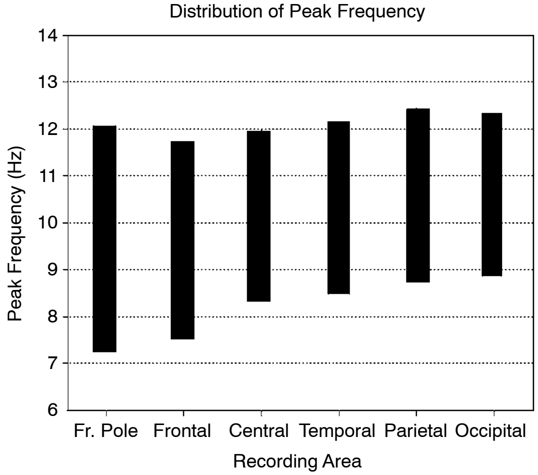
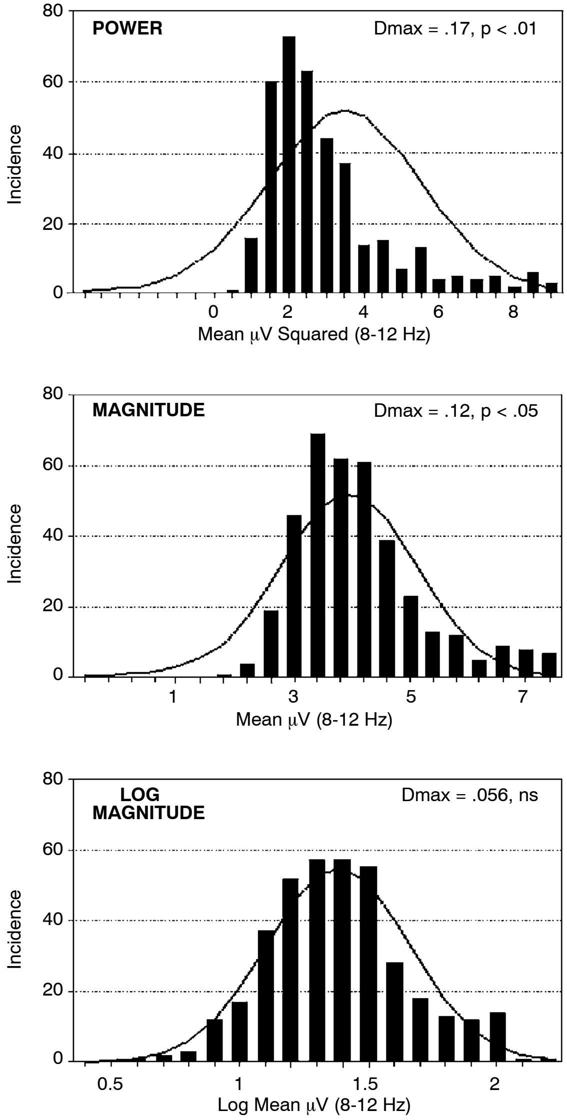


FIGURE 5. Distribution of three mathematical transformations of the same EEG data for 19 sites during a 2-min film-viewing condition (n = 20). The power transform results in a skewed distribution (p < .01, Kolmogorov-Smirnov test) whereas magnitude and log magnitude transformations produce marginally skewed and normal distributions, respectively.



Epoch Parameters

As mentioned above, spectral analysis usually involves Fourier analysis of the EEG signal. Fourier analysis, or Fast Fourier Transformation (FFT), requires that a signal be divided into segments, usually short in duration, called epochs. Underlying its use is the assumption that the signal analyzed will be stationary or time-invariable, but human EEG varies in character over time (Isaksson & Wennberg, 1976; Lopes da Silva, 1978; Praetorius, Bodenstein, & Creutzfeldt, 1977). Some researchers attempt to compensate by tailoring epoch lengths to signal properties (Lopes da Silva, 1978; Nuwer, 1988; Lehmann, 1989) or optimizing epoch duration for each psychological property under investigation (Walter, 1978; Gevins, 1984). The use of relatively brief epochs (1-2 s) is a general solution that overcomes the stationarity problem (McEwen & Anderson, 1975) as well as resolving other issues such as artifact control. As discussed in detail below, data loss from artifact rejection techniques is directly related to epoch length (Nuwer, 1988; Duffy, 1986; Duffy & Maurer, 1989).

Aside from these considerations, epoch duration does not appreciably alter study compatibility in the literature. In the studies surveyed, epoch length ranged anywhere from 0.25 seconds to 30 seconds or longer, with a median length of 2.5 seconds. Epoch length between 1 to 2 seconds should be short enough to capture psychological and psychophysiological fluctuations as well as being useful in estimating other spectral parameters of the alpha rhythm such as variability (Duffy, 1986).

The duration of EEG data acquired for each task (i.e., number of epochs multiplied by epoch duration) should be representative of task demands, resource allocation, and strategic factors. Investigations of continuous tasks such as mental imagery or problem solving typically record EEG for 30 seconds to 5 minutes. The concept of "macrostate" underlies such research, and the continuous EEG paradigm in general. According to the macrostate assumption or model, the various perceptual and cognitive operations associated with a mental or behavioral condition is thought to constitute a single distinguishable neurophysiological state with a distinct, reliable, and meaningful spectral pattern (Gevins, 1984; Gevins, 1986). Eyes closed and eyes open resting conditions are very good tests of this model. Both conditions are uncontrolled, self-paced, and may include dissimilar processes between subjects. Replications of these conditions do not usually differ topographically for most spectral parameters (e.g., Sterman et al., 1994; Kaiser, 1994), thus upholding the assumption.

Artifact Control

Electrodes do not differentiate electrical activity generated by cortex from that originating in extra cerebral sources (Gasser, Stroka, & Mocks, 1985).

Non-cerebral potentials generated by movements of the eye, tongue, face or neck muscles, heartbeat, or changes in skin conductance, can contaminate cortical activity (Barlow, 1986; Torello, 1989). Fortunately, low- and high-pass filters minimize most artifacts generated by muscles, changes in skin conductivity, and heart beat (Nuwer, 1988), but the problem of ocular artifact remains.

Eye blinks can last from 200 to 400 milliseconds and produce electrical magnitudes up to 800 microvolts, more than ten times the amplitude of cortical signals (Stern, Walrath, & Goldstein, 1984). The initial fast components of an eye blink can yield non-cortical electrical potentials with frequency components up to 10.5 Hz, well within the alpha range (Gasser et al., 1985; Brunia, Mocks, & Van den Berg Lenssen, 1989). Ocular artifacts can contaminate any recording site, though they are largest in frontal areas (Torello, 1989).

Artifact minimization and artifact rejection techniques have been developed to address the problem of eye movements and blinks. Artifact minimization encompasses those techniques in which contribution of suspected artifacts are estimated and removed from the EEG signal, usually achieved in the time domain (Kenemans, Molenaar, Verbaten, & Slangen, 1991; van den Berg Lenssen, Brunia, & Blom, 1989). Artifact rejection involves discarding epochs which are contaminated prior to averaging or further analysis. Elimination of epochs that contain damaging artifacts works well as long as epoch duration is relatively short and the presence of artifacts does not co-vary with experimental conditions (Berg, 1986).

Other techniques to reduce physiological artifact include instruction to the subject and provision of rest breaks. Subjects can be instructed to make conscious attempts to reduce eye blinks, especially during critical events (e.g., de Rijke & Visser, 1989). This approach essentially introduces an additional task component, which may distract the individual and interfere with the task under investigation (Semlitsch, Anderer, Schuster, & Presslich, 1986). An experimenter may also provide comfortable chairs and rest breaks for subjects to reduce ocular and muscular artifacts (Torello, 1989).

Although various procedures have been developed to reduce artifact in EEG recordings, no clear solution has emerged. Artifact minimization generally requires additional electrodes dedicated to detecting eye movements (Duffy, 1986; Coburn & Moreno, 1988), construction of a propagation model (Lins, Picton, Berg, & Scherg, 1993a; 1993b), estimation of variable time-delays, and other assumptions and obstacles that can hinder accuracy and effectiveness of this approach (Berg, 1986; Brunia et al., 1989). Using discriminant analysis, MacCrimmon, Durocher, Chan, Hay, and Saxena (1993) constructed a reliable, highly accurate, non-subjective method of detecting artifacts for use in artifact minimization methods; unfortunately, this computer-intensive method requires one hundred twelve features to be calculated off-line for each epoch. Artifact rejection has likewise been criticized as subjective (Mac-

Crimmon et al., 1993), unreliable, and susceptible to significant data loss (Barlow, 1986). The problem of artifact will likely continue to plague EEG science for some time to come.

Another common form of artifact can be attributed to data analysis. As mentioned above, spectral analysis of the EEG signal is usually achieved by means of an FFT of epoch values. Each epoch is a truncated segment of the EEG signal, which consists of 2^n data points. The truncation of an ongoing signal results in sharp edges (non-zero initial or final values) at beginning and end of the epoch. FFT of non-zero edges generates spurious frequency information about a signal, also called "leakage" (Jervis, Coelho, & Morgan, 1989). Mathematical functions called "windows" or "frames" can be applied to epoch values to taper data at epoch edges and reduce the effect of leakage. A 4-term Blackman-Harris was used in this study (Harris, 1978). While a tapering function effectively eliminates leakage, it results in artificial broadening of frequency peaks (smearing), a reduction of signal power (Jervis et al., 1989), and preferential sampling of the EEG signal. Use of multiple overlapping windows can remedy the effect of preferential sampling (Davidson et al., 1990; Sterman et al., 1994), but this practice is rare. A design using wide frequency bands, within-subject comparisons, and relatively stable psychological conditions, will not be adversely affected by a tapering function.

Appropriateness of Parametric Statistics

Although inferential statistics are required for generalizing sample results to a subject population, Etevenon et al. (1989) and others have proposed the use of nonparametric tests in response to the skewness inherent in physiological data. However, as mentioned above, the log transformation of alpha magnitude results in normal distributions. Physiological data also rarely satisfy the independence assumption for statistical tests including the Analysis of Variance. Applying a statistical correction to compensate for nonsphericity of physiological data is recommended (Greenhouse & Geisser, 1959; Huynh & Feldt, 1976; Keselman & Rogan, 1980). As the Greenhouse-Geisser correction is theoretically and empirically conservative and often results in Type II errors (Klimesch, Pfurtscheller, Mohl, & Schimke, 1990), the Huynh-Feldt correction is recommended for QEEG analyses. Depending upon design, additional statistical controls may be required. For instance, a Bonferroni or similar correction can be used to counteract the negative effect multiple statistical tests can play on experiment reliability.

CONCLUSION

Despite these and other methodological obstacles, an incredible amount of reliable and worthwhile research of the human EEG has been accomplished, particularly during the last decade (see review of clinical QEEG by Hughes & John, 1999). Nevertheless, the state of QEEG remains akin to chemistry before the discovery (or invention) of the periodic table. Some findings parallel others, but many seem completely out of place, and none of it makes sense as a whole. The field of EEG biofeedback suffers from some of these issues, and by comparison, and as the numbers of neurofeedback investigators grow, so will the issues and volume of the critics. Clearly quantitative topographic EEG holds great promise for the study of higher cognitive functions and assessment of cognitive and attentional dysfunction, possibly more so than any other approach in common use today. But we lack a compelling periodic(ity) table in which to provide context for our work.

In the past forty years, a variety of approaches have been used to investigate spectral correlates of attention and higher cortical functions. As every investigator is well aware, he or she is faced with numerous methodological choices–in terms of reference electrodes, recording electrodes, epoch parameters, frequency bandwidth, data transformation, and artifact control, to name a few. Reliability, practicality, and relevance to the psychological or psychophysiological phenomenon under investigation govern most of these choices. Hopefully this essay provides a basic framework that can also assist in this decision-making process.

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